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Exploring the Benefits of Combined State-of-the-Art Tools for Multi-View Systems Modeling

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Abstract

The growing pressure to adapt to changing conditions, to accelerate the adoption of new technologies, and to develop innovative products and systems in significantly shorter time frames has created new challenges. One consequence is the increased need to integrate system-level and detailed-level design more closely.

EXPEED, short for *EXploring the Potential benefits of systEms modEling state of the art Design tools*, was launched under the Swedish National Aeronautics Research programme to explore how recent research-based methods and tools can be combined to support decision-making, particularly in balancing trade-offs between different perspectives and disciplines. The initiative was supported by GKN Aerospace in Sweden, which provided a recent public reference case to a research team from Chalmers (SE), Cranfield and Cambridge (UK), and NASA (US).

The six-month project consisted of a series of short studies investigating how and to what extent manufacturability considerations should be incorporated into conceptual-level (systems analysis) design. The findings, summarized in this report, provide insight into how diverse approaches and tools can be integrated to address real-world challenges. The key takeaway is the value of bringing together experts and their tools, not only to resolve initial challenges of terminology and context but also to tackle integration issues that arise when combining different methods. While exploratory in nature, the project demonstrated the importance of using a realistic reference case. Through this example, one notable advantage of combining methods is that the different assumptions and perspectives built into each tool help uncover and account for effects that might otherwise be overlooked.

Keywords: engineering design, systems analysis, systems engineering, systems modeling, functional modeling, bayesian networks, visual analytics, generative artificial intelligence, large language models, design for manufacturing

List of Acronyms

EXPEED	EXploring the Potential benefits of systEms modEling state of the art Design tools
E FM	Enhanced Function Means
AIT	Assembly, Integration and Testing
TOICA	Thermal Overall Integrated Conception of Aircraft
CRESCENDO	Collaborative and Robust Engineering using Simulation Capability Enabling Next Design Optimization
VDD	Value Driven Design
DSM	Dependency Structure Modelling, or Design Structure Matrix (used interchangeably)
MDO	Multi-Disciplinary Optimization
CPM	Change Propagation Method
APROCONE	Advanced PROduct CONcept analysis Environment
DIAS	Development of Interdisciplinary Assessment for manufacturing and deSign
DIFAM	
CHEOPS	Consortium for Hall Effect Orbital Propulsion System
FUTPRINT50	FUTure PRopulsion and INTegration towards a hybrid-electric 50-seat regional aircraft
SBD	Set-Based Design
ONEheart	Out of cycle NExt generation Highly Efficient Air Transport
LLM	Large-Language Model
MDAC	Multi-Disciplinary Analysis Client
PDOPT	Probabilistic Design and Optimization
DSE	Design Space Exploration
BN	Bayesian Network

1. Introduction

Increasingly stringent sustainability and economic requirements and mounting geopolitical concerns drive the need for rapid innovation within the aerospace industry. In parallel, technology development in different areas, such as lightweight heat-resistant materials and increased electrification open up opportunities for new novel solutions. This provides several challenges when rapidly integrating the technologies into complex systems. Traditionally, aerospace design has relied on incremental improvements, with safety, resilience, and performance as central guiding principles. Over the past half-century, confidence in meeting safety, resilience, and performance targets has steadily grown, building largely on previous designs. However, radical and disruptive innovation risks undermining this accumulated design confidence, potentially jeopardizing safety, resilience, and performance. The key challenge, therefore, is to integrate radically new solutions and technologies while continuing to meet the sector's uncompromising requirements for safety, resilience, and performance. In addition, the pressure to minimize implementation time is higher than ever.

In NASA terminology, Systems Analysis is used to denote the earliest phase of design (Cavanaugh et al, 2006), where concepts are being defined on an overall level to meet the expectations of the intended operation or mission. Systems Engineering then covers the effort necessary to deliver a complete definition and verify requirements of the product or system, to a state where it can be manufactured and produced. To align with engineering design literature, where conceptual design is succeeded by detailed design (or embodiment design) for the same efforts we clarify that the EXPEED project considers the overarching systems design effort, combining both the systems analysis phase and the systems engineering effort. In particular, we address the role of technology in the different phases. Technology is critical to defining the overall systems architecture, the detailed definition of the product, and the detailed definition of how the product is realized, i.e. the manufacturing phase. We also use the term production to indicate a wider notion of the phase where the product or system is manufactured. Thus, production includes also the material flow, organization and supply chain activities. From a design perspective, production aspects can be important, since real world constraints of material supply and other related factors, can be seen as constraints. We recognize that all these aspects are not traditionally addressed simultaneously, but only partially using state-of-the-art modeling capability. Across all stages of development, technology plays a central role, as technological choices influence system-level architectures, detailed solutions, and manufacturing processes alike. In EXPEED, the underlying idea is to connect the three views of technology, product/systems, and production, as the dependencies and rate of change on the system level require multiple views to be evaluated simultaneously. Also, as entire systems are being more tightly integrated, detailed design decisions may have a direct impact on system-level behavior and vice versa.

The EXPEED project was initiated to combine state-of-the-art engineering design methods and tools. The aim is to explore means of improving knowledge creation early in development to reduce the risk of not meeting critical targets. The project, led by Chalmers, was conducted in close collaboration with GKN Aerospace, Cranfield University, Cambridge University, and the Systems Analysis and Concepts Directorate (SACD) and Engineering Directorate at NASA Langley Research Center. EXPEED took an approach to explore how different domains and viewpoints govern the conditions for trade-offs from a multi-view perspective. The technology view is compared to the product and systems view and the production view as shown in ***Figure 1***.

In the **product/system view**, as shown in ***Figure 1***, the focus is on iterating the mission and operational needs, and on an architectural level, to identify solutions that have the potential of meeting these needs. In this view, systems analysis, functional analysis, etc., are central. The **technology view** focuses on technologies that realize desired functions in products, systems or processes. One example is the technologies that realize thermal management needs in an aircraft. Other examples can include lightning protection, and multifunctional materials. In addition, technologies for manufacturing and production can be studied, such as additive manufacturing that enables net shape manufacturing, advanced geometries, part reduction and repair technologies.

Finally, the **production view** is central for manufacturing companies focusing on actual manufacturing and production. Although production comes after the product and system have been designed, the production view is important to offer both novel and feasible ways of realizing advanced systems. One example is that printing technology can be used to manufacture rocket nozzles, reducing part count and weight.

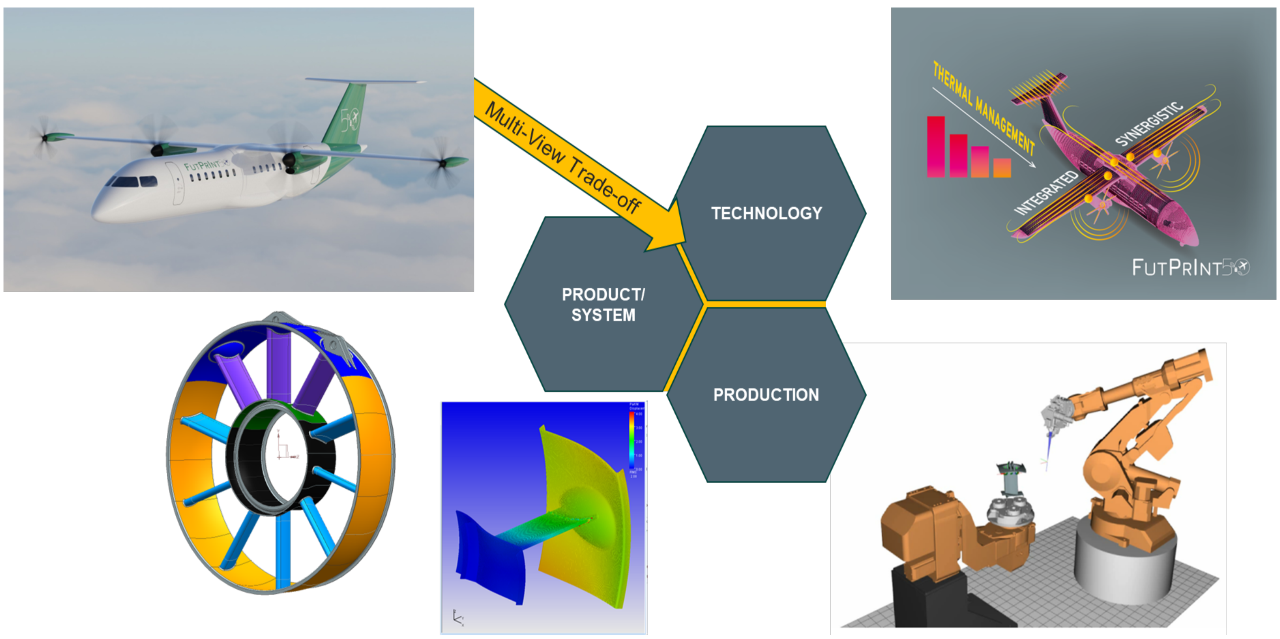

Figure 1 The EXPEED concept; Exploring multi-view trade-offs between product and system (a hybrid-electric regional aircraft, or a turbine rear structure of the propulsion system, or a vane/engine component), and production (a welding robot for engine component assembly), and technology (novel thermal management systems). Illustrations used from FUTPRINT50 (European Commission, 2023b) and DIAS (European Commission, 2023a) projects with permissions.

Production and manufacturing aspects are focused in what NASA calls Engineering where Systems Engineering is a key function. Other functions within Engineering are: designing the needed flight software, electrical systems including boards and harnessing and power for the distributed components, mechanical design (all the physical components from basic brackets to the whole wing and fuselage design), assembly, integration and testing (AIT) (when all the various parts and pieces come in and need to be carefully assembled, integrated into larger components, and tested at component and whole system levels), etc. Systems Engineering integrates all the functions of Engineering to ensure they are effectively completed.

There are examples of studies in the literature where the choice of combination of design parameters of an engine component impacts the ability to be manufactured (Isaksson et al., 2021). In other studies, the choice of manufacturing tolerance in accordance to flight condition requirements can impact the aerodynamic performance of a wing as well as its production cost (Kim et al., 2022). Most recently, the impact of aircraft performance and operation ability were studied when different energy storage technology is utilized on a hybrid electric regional aircraft (Spinelli et al., 2025; Spinelli et al., 2023b). In all cases, “partial” multi-view trade-off analyses revealed nontrivial insights.

In EXPEED, the fact that different tools and methods are used in the different views is addressed. Early in the EXPEED effort, we raised questions regarding how and when to bring in the different perspectives from each of the three views (technology, product/system, and production) to enable multi-domain trade-offs and decision making. For example, *when and how to consider manufacturability in design/product development?* In this report, we present seven different tools expressing different methods in systems modeling, systems analysis, design space exploration, multidimensional data visualization, decision making, and agentic artificial intelligence. These tools and methods were developed through several national and international collaborative research projects over the past 15 years. Integration of the tools facilitated the exploration of multi-view trade-offs and examined the connectivity of technology, product/system, and manufacturing. We will conclude this report by sharing our insights and learnings, as these were discovered through this multi-national collaborative effort.

2. Background and Rationale

The primary focus of this study was to benefit from the work and research conducted through numerous research projects over the past 15 years in the aerospace field, including those from universities, tier 1 industries, and small to medium enterprises. ***Figure 2*** shows the continuation of the research projects at national and international levels. We should note that, within this report, we do not present an exhaustive record of the literature.

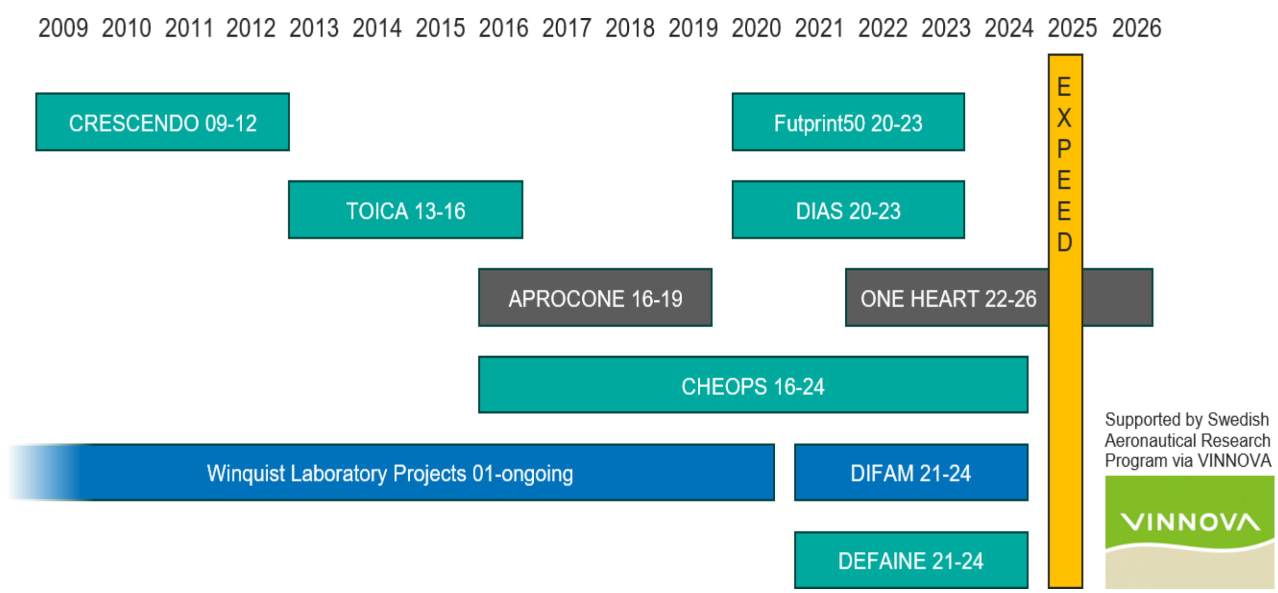

Figure 2 Previous national and international programme outcomes which are aggregated in the EXPEED project (green - EU, grey - UK, blue - SE).

2.1 TOICA and CRESCENDO

The aim of the European Framework TOICA (Thermal Overall Integrated Conception of Aircraft) project (European Commission, 2016), led by Airbus, was to radically change the way thermal studies are performed within aircraft design processes. Several modeling methods and tools, previously developed within the CRESCENDO (Collaborative and Robust Engineering using Simulation Capability Enabling Next Design Optimization) project (European Commission, 2012), were combined with new initiatives into an integrated process. These were Value Driven Design (VDD) (Isaksson et al., 2013; Kipouros & Isaksson, 2014), Function Means Modelling (E FM) (Raudberget et al., 2015), Design Structure Matrix (DSM), Change Propagation (CPM) and risk analysis (Clarkson et al., 2004), Physics- Based Simulations and Interactive Multidimensional Data Visualization (Kipouros & Isaksson, 2016; Kipouros et al., 2013). The relevant results to EXPEED were the ability to conduct quantified assessments and trade-off analyses of alternative thermal architectures considering the impact on Product- and Production-Performance.

2.2 APROCONE, DIAS, and DIFAM

Within the projects APROCONE (UKRI, 2020), DIAS (European Commission, 2023a), and DIFAM (Vinnova, 2024) the main focus was to enable the study of manufacturability and product performance trade-offs in early phase exploration. To achieve this, non-standard simulations (welding simulation, weld-paths, weld accessibility) were embedded into the process (Isaksson et al., 2021) and aircraft performance vs. weld accessibility trade-off was studied. In the APROCONE project, different disciplinary data were fused together using Visual Analytics within the context of aircraft wing performance vs. manufacturing cost of technology (Kim et al., 2022; Piotrowski et al., 2019).

We realized that a combination of methods, tools, and data to account for performance and production co-development was possible and necessary to offer the exploration of multi-view trade-offs. The insights and solutions were superior to any other result discovered when the views were studied in isolation. These results gave the know-how in combining and synthesizing different methods and tools together for complex trade-off analysis.

2.3 CHEOPS

In the EU project Consortium for Hall Effect Orbital Propulsion System (CHEOPS) (European Commission, 2021) the main objective was to push the deployment of electric propulsion technologies for different satellite applications by demonstrating functionality and realizability. One aspect was how to compare the relative benefit (value, cost) of new solutions that add functionality to existing solutions. Since satellite scenarios now include production of higher volumes of satellites (thousands) versus traditional production volumes that are in the order of tens. As such, the importance of producibility becomes more important relative to what the manufacturers were normally used to.

The main effort for participating manufacturers was to design, build and demonstrate propulsion concepts for three alternative satellite operation situations. In parallel, Chalmers developed a way to compare alternative production architectures and methods to evaluate system level satellite performance. This Value Driven Design approach enabled performance to cost trade-offs (Panarotto et al., 2022). The resulting Value Driven Design model allowed comparing the suitability of alternative product/system architectures in a way that compensated for alternative architectures, functionality and performance relative to different mission scenarios.

2.4 FUTPRINT50

In the FUTPRINT50 (FUTure PRopulsion and INTegration towards a hybrid-electric 50-seat regional aircraft) (European Commission, 2023b) Horizon project, the key enabling technologies for regional aircraft electrification were investigated and developed. For this purpose, a design methodology was developed, which synthesized Set Based design (SBD) and Multidisciplinary Design Optimization (MDO) principles. The design space exploration time was reduced by 80% (Spinelli et al., 2022, 2023c, 2023b); and, the methodology set the basis for the Bayesian Networks approach developed in a later research project. Further to these benefits, non-trivial design trade-offs between technologies and aircraft (Krupa et al., 2023) were possible to be discovered, analyzed, and understood.

2.5 ONEHeart

In the project ONEheart (Out of cycle NExt generation Highly Efficient Air Transport) (UKRI, 2025), rapid aircraft design methods and tools are studied and developed. An extended SBD and MDO approach for complex systems trade-off probabilistic exploration was developed using Bayesian Network inference (Georgiades et al., 2019; Spinelli & Kipouros, 2024). The method creates several opportunities for it: 1) enables the user to explore the trade-off between performance and sustainability criteria (Spinelli & Kipouros, 2025a); 2) allows design of requirements (Spinelli & Kipouros, 2025b); 3) enables the synthesis of a large volume of data into a unified context; and, 4) allows the fast utilization of such information to explore complex queries that enable deeper understanding of the system in question.

3. Approach

The EXPEED project, led by Chalmers University of Technology and funded by the Swedish Innovation agency, called Vinnova, was an international collaboration between Sweden, the United Kingdom, and the United States of America. Besides the desk-based research, several joint workshops were conducted both online and in person. The overview of the activities is shown in ***Figure 3***.

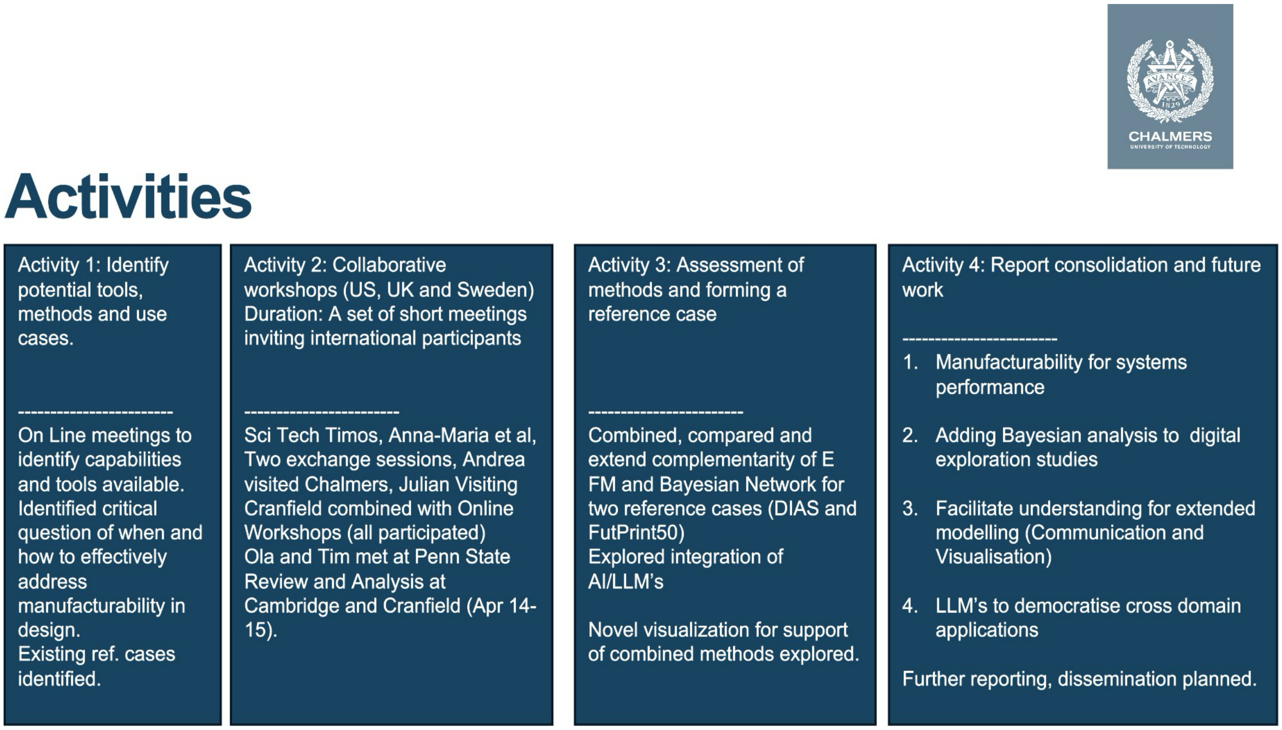

Figure 3 Overview of the EXPEED activities and approach (Snapshot from final presentation event)

At the online kick-off meeting the objective of the EXPEED project was stated: to investigate the potential to combine state-of-the-art engineering design methods and tools to better inform system developers who seek to build integrated concepts. Then, three specific goals were agreed among the participants. These were a shortlist of methods and tools, a systems design and integration reference case, and a list of gaps in systems engineering design integration capabilities. Through the discussions, some expectations and open questions were raised, such as how to enable and support multi-view perspectives and trade-off analysis. In particular, how to facilitate an advanced components manufacturer's view (such as GKN Aerospace) and a systems developer's view (such as NASA) in early development phases.

3.1. Workshop 1

The objective of the first online workshop was to identify potential tools, methods, and use cases in the context of EXPEED. Each partner presented and proposed relevant tools and methods. A discussion followed between the partners, and some reflections were captured. A driving question was identified: *When to consider manufacturability and producibility in modern product development?* and a further important question was raised about the terminology and communication of systems analysis and systems engineering. Finally, the need for a suitable reference case study was identified as the next step and a template to capture the information from all partners was created and shared. GKN suggested using the industrial case developed in the DIAS project (Martinsson Bonde et al., 2022). Another case suggested was from the FutPRINT50 Project. The overview of the data set context is shown in ***Figure 4***.

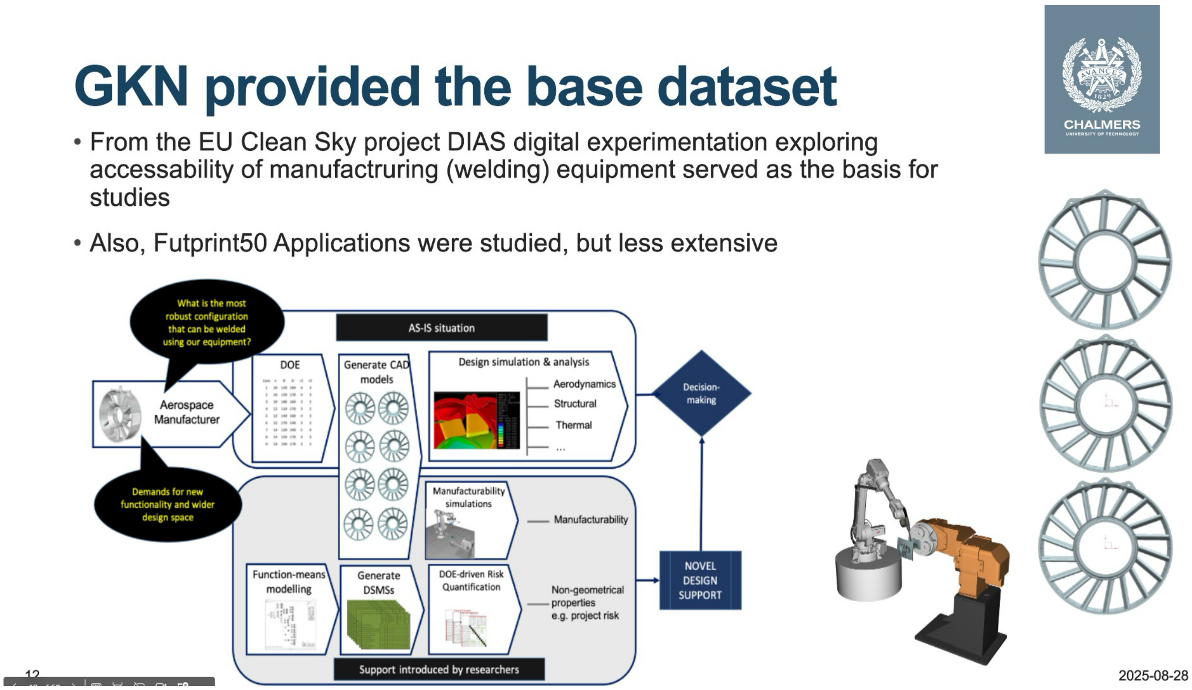

Figure 4 Original slide from Workshop 1, introducing the GKN case from the DIAS project.

The DIAS reference case from GKN Aerospace provided data for a realistic design space exploration study of a Turbine Rear Structure of a typical jet engine for commercial aircraft. Basic structural and aerodynamic loads and criteria were complemented with data to investigate the welding feasibility since the rear structure typically is a weld assembly. Accessibility of welding equipment, distortions and stresses induced when welding, etc., are typical factors that have a significant influence on weldability (time, effort, cost, quality) and can influence the superior systems (jet engine) architectural design decisions.

The FutPrint50 reference case offered data to study technology trade-offs for thermal management systems or energy storage systems in a hybrid-electric regional aircraft.

3.2. Research Exchange

A case study from the DIAS project was identified as suitable for the EXPEED project. Two research exchange visits were organized between the UK and Sweden, primarily between Chalmers University of Technology, Cranfield University, and the University of Cambridge. Check-in and check-out online sessions were scheduled during both visits where all EXPEED project participants participated. Through the visits, collaborative technical investigations were enabled where methods and tools were used and integrated using reference case data. The complementarities and synergies between the different tools were explored and new proposals were identified. Results from previous projects were enriched with new visualizations and expression of queries, and new insights were discovered. The opportunity from these short exchange sessions offered the possibility to develop and adjust a few software extensions and new developments to address some of these challenges. An example is shown in ***Figure 5***.

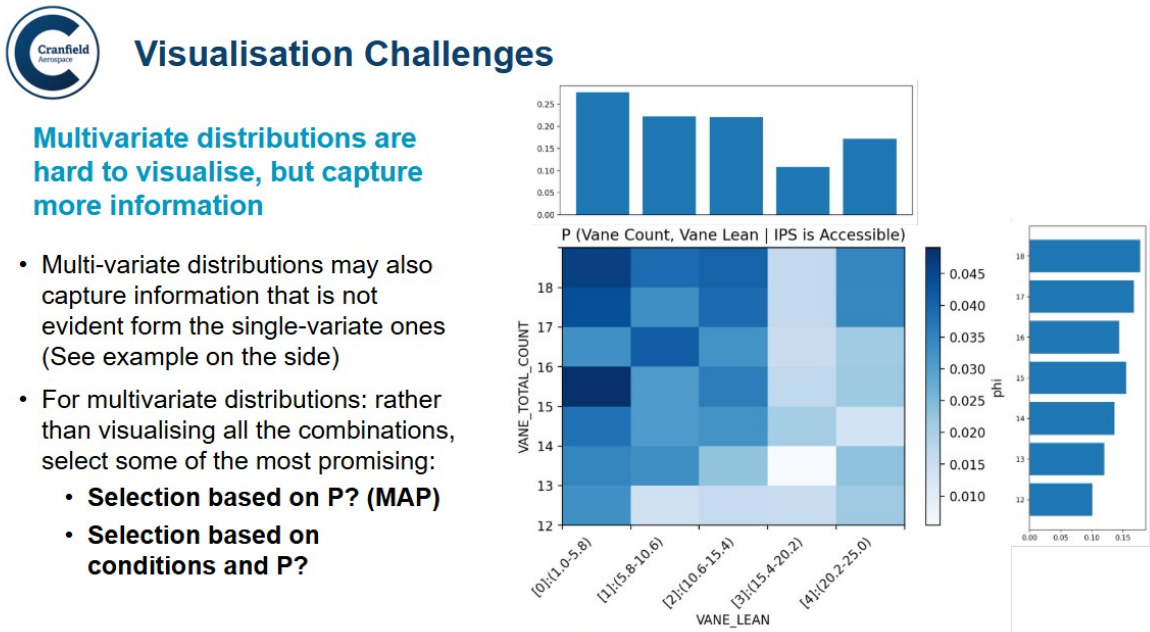

Figure 5 An example of a visualization challenge. The result on the right of the figure shows the probability distributions of parameters that satisfy manufacturability requirements - Bayesian query: Which values of Vane Count and Vane Lean should I use if I want a weldable design?

The results were insights and learnings that informed the team on the next steps and opened ideas for how to exploit the synergies further. To exemplify, the Bayesian Network approach was adopted to synthesize different datasets within the reference case study. Here, questions on how to develop an extended Bayesian Network to synthesize data from different studies were discussed. It was also discussed how parallel coordinates visualization could be extended to represent probabilistic distributions resulting from the Bayesian Network analyses. Finally, during the discussions, the inspiration and potential use of LLM's to automate code execution, to store user knowledge or in other ways improve the ease of use of these specialized methods were discussed.

3.3. Workshop 2 - Final Analysis

After the completion of the research exchange visits, the work and insights were consolidated and communicated with all partners in an online workshop. Two new developments were demonstrated as shown in the list below:

- Visualizing probability distributions in Bayesian Networks using enhanced Parallel Coordinates.
- Applications of Bayesian Networks for engineering design tasks.

The analysis further suggested further work on both the application of Bayesian Networks in function-means architectures, data-fusion, the use of LLM's and advancing visualization techniques to support interpretation interactively.

3.4. Presentation at the Digital Engineering Forum of NASA

Final results were disseminated via an on-line seminar to the NASA Langley Digital Engineering community and additional feedback was received. Some of the questions that were discussed were:

- What is the complexity of building Bayesian Network models?
- How to account for -ilities when different levels of data fidelity are available?

4. Methods and Tools Studied

Based on the previous projects, we selected a sample set of tools relevant to the EXPEED project and with sufficient expertise among the participants to do meaningful studies in a limited time. In this section, details of the tools and methods used in EXPEED are briefly explained. Other research providing relevant tools in similar areas can be used, and some of these are briefly referenced in this section as well.

4.1. Multi-Disciplinary Analysis Client

The Multi-Disciplinary Analysis Client (MDAC) is an open source visual analytics software used to evaluate many alternative design points concurrently (Martinsson Bonde, 2025b). MDAC contains conventional parallel coordinate plots and scatter plots that can be interacted with, along with implementations of methods developed through research such as similarity analysis (Martinsson Bonde et al., 2023). One of the strengths of parallel coordinates is the ability to visualize data from many aspects simultaneously, and to interact with the data by screening the design space using filters. As such, this approach to visual analytics enables engineers to consider technology, production, and product/system views concurrently, and helps in identifying and managing trade-offs among them.

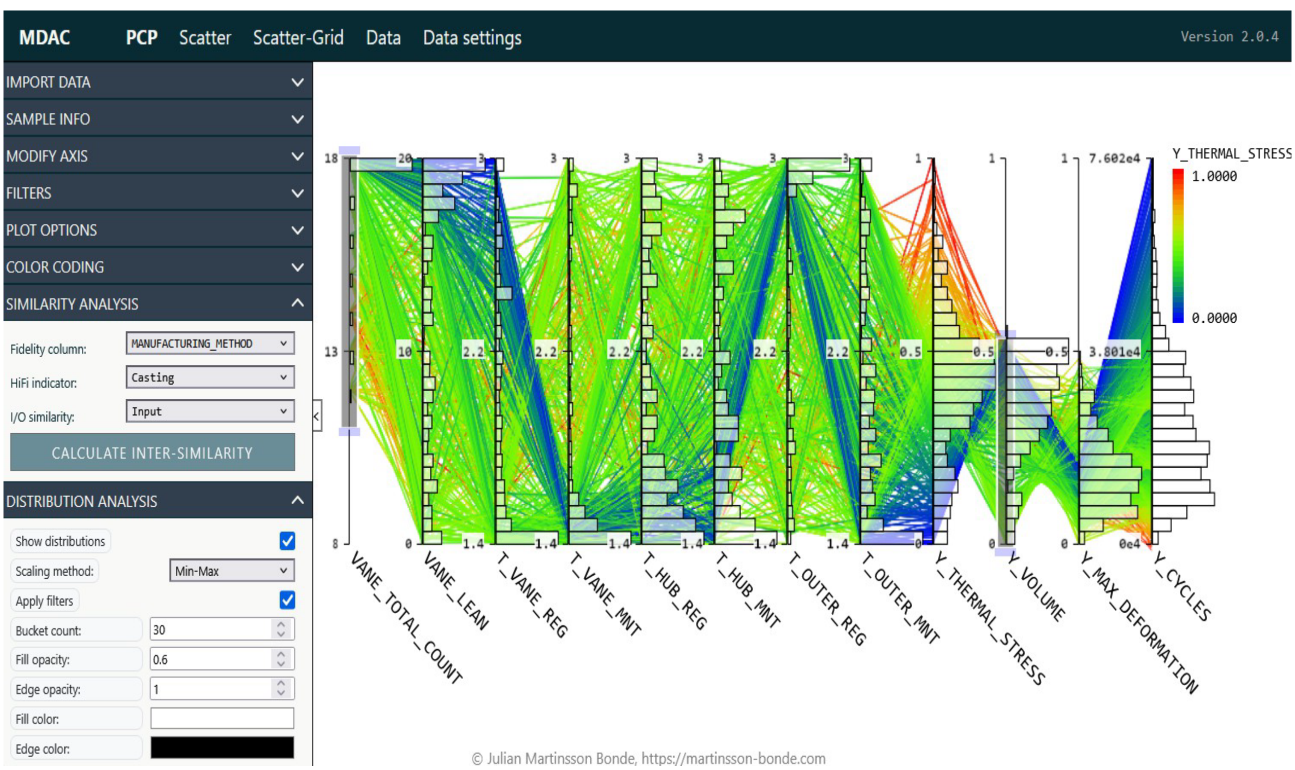

Figure 6 Screenshot of MDAC visualizing a design space using parallel coordinates, and how the data within that design space is distributed through superimposed bar charts.

4.1.1. Contribution

MDAC has served as a software platform on which alternative visualization techniques have been experimented with. This has enabled rapid testing of new visual analytic methods and alternative design evaluation metrics. This includes the development of similarity metrics used to evaluate the trustworthiness of existing data (Martinsson Bonde et al., 2023, 2024) and visualization of data distributions within design spaces, a sample screenshot of which is visualized in *Figure 6*.

4.2. Trinity

Trinity is a functional architecture software used to decompose systems using function-means modeling (Martinsson Bonde, 2025a). The use of function-means modeling enables Trinity to represent multiple alternative system configurations using the same model. These alternative configurations can then be analyzed within Trinity using its implementation of classical design structure matrices and change propagation (Clarkson et al., 2004).

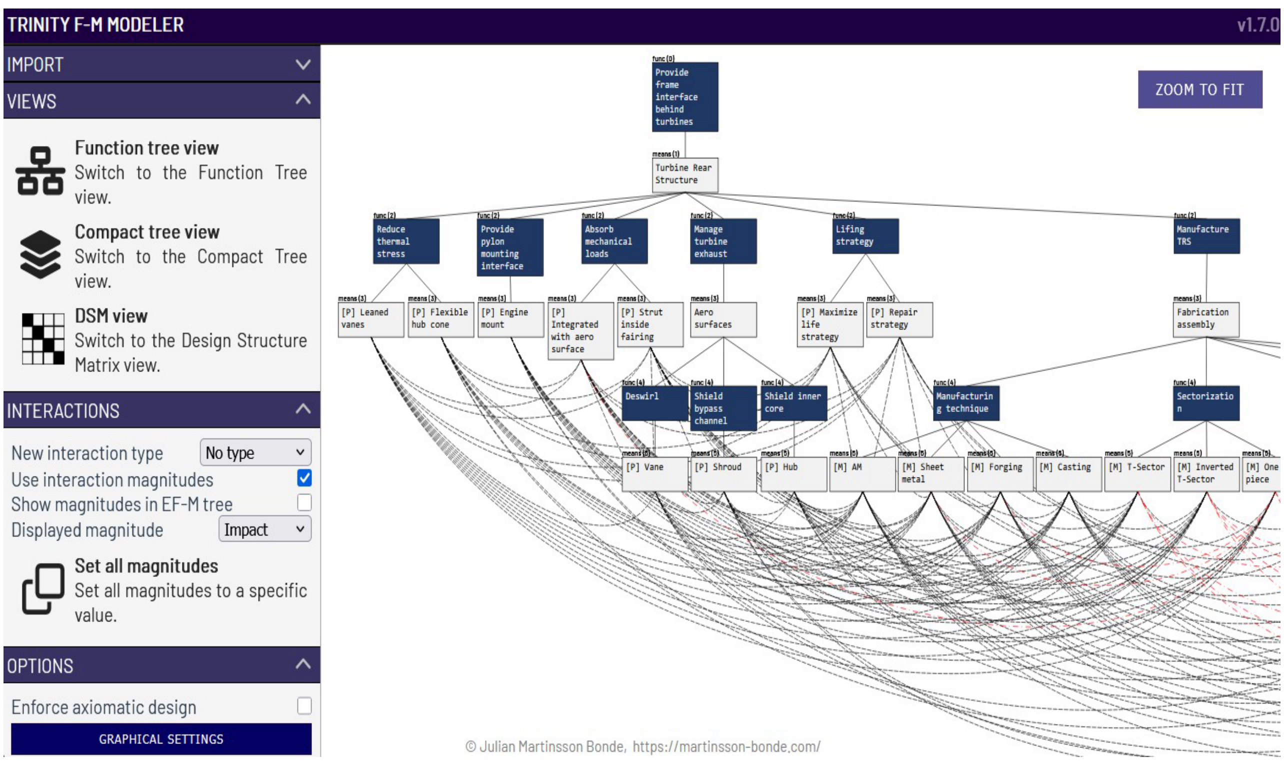

Figure 7 Screenshot of Trinity visualizing the functional decomposition of the DIAS case study used in EXPEED representing dependencies between product functional components, and manufacturing processes.

4.2.1. Contribution

Trinity enables functional decomposition of the product, or system of interest. This type of modeling enables the consideration of not just the product/system domain, but also of the production domain. Through collaboration between Chalmers and Cambridge, Trinity has been used as a bridge between EF-M function modeling, developed at Chalmers (e.g. Müller et al., 2019), and change propagation analysis, developed at Cambridge (Clarkson et al., 2004). This bridging of methods has enabled evaluations of, for instance, how the product/system and production is coupled, and how trade-offs are formed between them (Martinsson Bonde et al., 2025). An example of modeling both the product and its production concurrently can be seen in ***Figure 7*** where the curved lines represent dependencies and interactions within an aero engine component, and its production process.

4.3. Probabilistic Design and Optimization

Probabilistic Design and Optimization (PDOPT) is a framework for design space exploration. It combines principles of Set-Based Design with probabilistic machine learning to accelerate the identification of feasible design options for a given problem (Spinelli & Kipouros, 2024). Design problems are framed as constrained optimization, where feasibility requirements are casted as constraints and desirability requirements and criteria are transformed into objectives. This results in a family of design solutions which are locally optimal but maintain sufficient variance for a thorough initial design space exploration in reasonable time. ***Figure 8*** presents a flowchart of the PDOPT framework. The tool is open-source and available online (Spinelli, 2023a).

4.3.1. Contribution

In FUTPRINT50, PDOPT was extensively used to analyze the interaction between energy management strategy and the hybrid-electric aircraft system. This resulted in several recommendations such as identifying the most efficient parametrization of the energy management schedule (Spinelli et al., 2023c), exploring the trade-off between the battery durability and the environmental compatibility of the hybrid-electric aircraft (Spinelli et al., 2023c), and suggestions to the directions in technological development of energy storage (Spinelli et al., 2025).
With a suitable model that encompasses Technology-, Production- and the Product-views, PDOPT can provide insights by exploring all the combinations of the design variables and how the multiplicity of the design space changes depending on the imposed requirements. As demonstrated in the analysis of batteries for hybrid-electric aircraft (Spinelli et al., 2025), technological parameters are incorporated in the multi-view trade-off with the system design itself, yielding new insights.

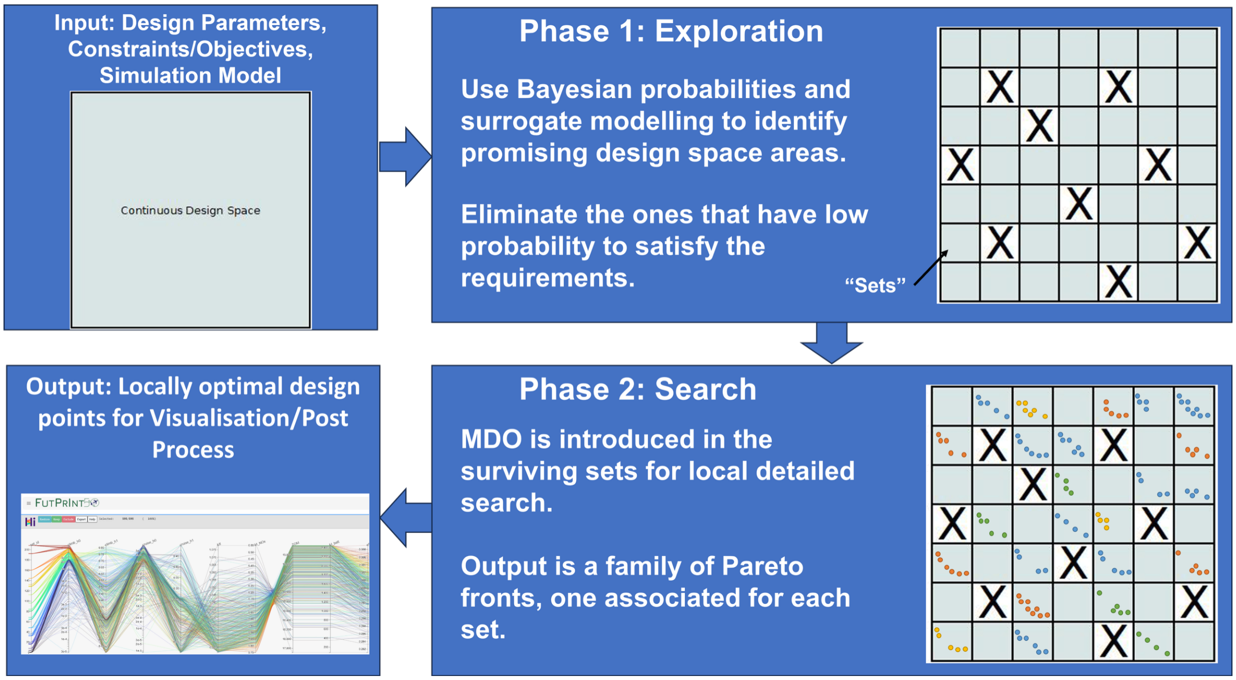

Figure 8 Flowchart of the PDOPT framework showcasing the process of a set based MDO approach within a FUTPRINT50 case study combining product and technology views.

4.4. Design Space Exploration with Bayesian Networks

Design Space Exploration (DSE) usually occurs at the beginning of the design cycle, where the overall concept is still fuzzy and undefined. Bayesian Networks (BN) have been proposed as a useful DSE tool, since it is capable of handling decision-making problems with a high level of uncertainty (Spinelli & Kipouros, 2025b; Spinelli et al., 2024). The user trains a probabilistic model which encapsulates the cause-and-effect dependency between the variables. With this model, it is possible to ask queries regarding the probability of a variable's state (or multiple ones), given a set of conditions (see

Figure 9 for examples). Details on how to construct Bayesian Network queries for the purpose of engineering design can be found in (Spinelli & Kipouros, 2025b). At the time of writing, this methodology is being integrated in the PDOPT codebase in an experimental dedicated branch (Spinelli, 2025).

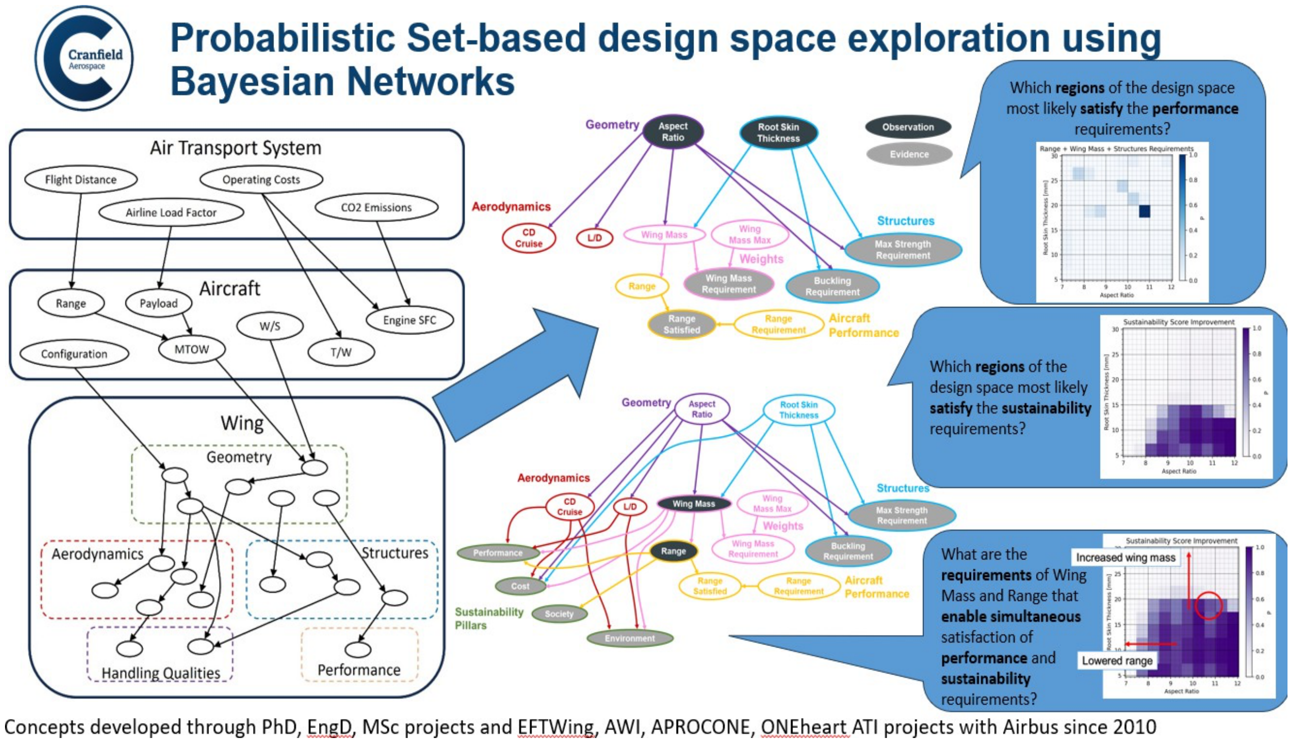

Figure 9 Example application of a Bayesian Network for the ONEheart wing design test case.

4.4.1. Contribution

The application of Bayesian Networks to multidisciplinary engineering design problems has been explored in Project ONEheart (***Figure 9***), specifically using a wing design case study that evaluates both technical requirements (cost, weight) and sustainability criteria (Spinelli & Kipouros, 2025a). The research revealed that performance requirements were too restrictive and incompatible with sustainability goals, while showing how Bayesian Networks can help engineers understand system interactions and revaluating requirements, considering a holistic view of the system within its context. The queries presented use heat maps to show high probability areas in the design space presented. The model acts as an intermediary between different disciplines, allowing experts to communicate and reducing the need to make assumptions within the development cycle. This potentially can reduce the rework caused by errors, saving time and costs.

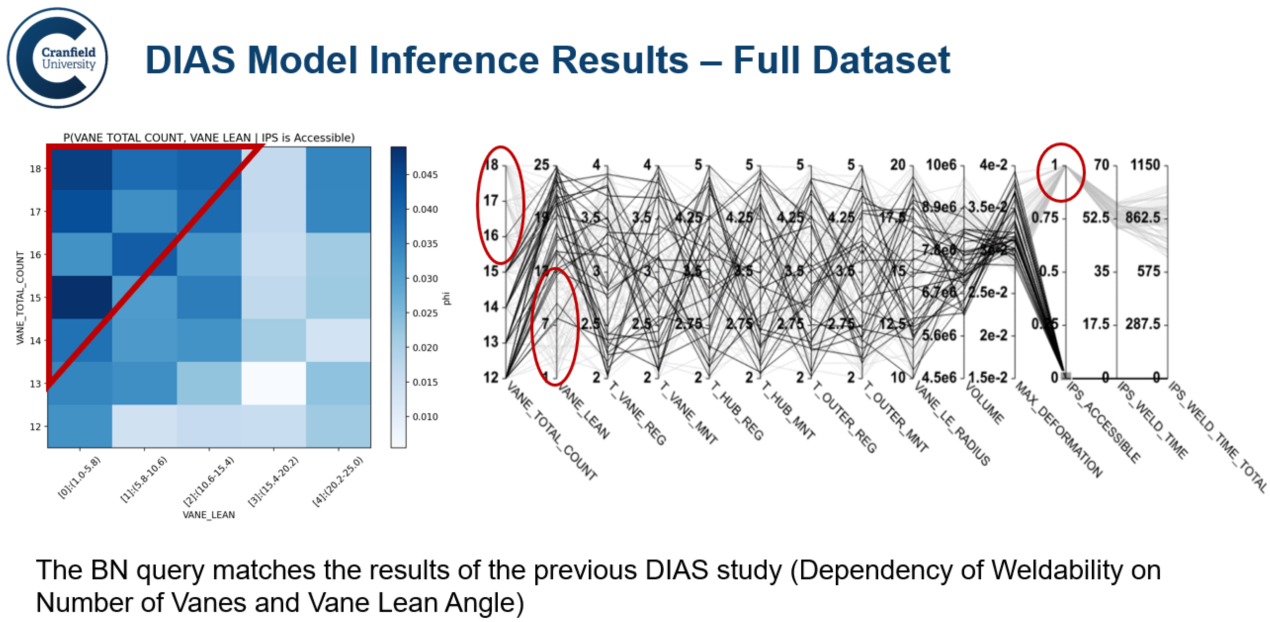

Figure 10: Example of a BN query trained on the DIAS dataset, with comparison to the source data.

Within the EXPEED workshops, this methodology has been applied on the DIAS project dataset to compare its results with the other approaches (*Figure 10*). The developed network model integrated the manufacturability aspect with the product design requirements, through the fusion of two different datasets. This synthesis has the potential of delivering a more integrated multi-view tool for a holistic analysis of the product under design. Indeed, the diagram would provide a bird's eye view of the cause-and-effect chain between the different aspects (technology, product design, production) and still provide quantitative information for estimating the effects of each component on the overall system.

4.5. Other Methods and Tools

4.5.1. PDOPT Decision Making Visualization Tool

The decision-making environment is an interactive webtool developed in parallel with PDOPT (Spinelli et al., 2023a). It combines Parallel Coordinates diagrams with Scatter plots, as an alternative to MDAC as used in the EXPEED studies. The user can isolate any datapoint and propagate the selection to the other diagrams. This interactivity enables the user to explore the dataset and draw information from it rapidly. An example of this visualization tool can be found in (Spinelli, 2023b). This was demonstrated within project FUTPRINT50 with a complex dataset of 50 parameters of hybrid-electric aircraft.

4.5.2. Cambridge Advanced Modeller

The Visual Analytics Modelling capability within the Cambridge Advanced Modeller (EDC, 2025) was developed to facilitate multidimensional data visualization and interactive analysis to support the decision-making process. What is unique within this implementation is the embedded Machine Learning model, based on Gaussian Process

Emulation, which can be built on the fly based on the loaded dataset and according to the choice of the user of the number of input and output parameters of the model (Piotrowski et al., 2019). This model can then be used to test hypotheses based on the findings of the first analysis, and then extend to insights and knowledge about the problem in question. An example within the FUTPRINT50 project can be found in (Spinelli et al., 2023a).

4.5.3. OpenMDAO

OpenMDAO (Gray et al., 2019) is an open-source high-performance computing platform for systems analysis and multidisciplinary optimization, written in Python. It enables you to decompose your models, making them easier to build and maintain, while still solving them in a tightly coupled manner with efficient parallel numerical methods. The OpenMDAO framework facilitates faster, more stable design optimization, rapid development of new analysis tools, and tight integration of high-fidelity analyses into system level models.

4.5.4. OpenVSP

OpenVSP (McDonald & Gloudemans, 2022, 2025) is a parametric aircraft geometry tool. OpenVSP allows the user to create a 3D model of an aircraft defined by common engineering parameters. This model can be processed into formats suitable for engineering analysis. OpenVSP is an open-source project.

4.5.5. Club Design

The Value Driven Design methodology, used in CHEOPS, has recently been implemented into a modelling environment to enable practical use. Here the high-level stakeholder expectations and needs are systematically captured and linked to the designable parameters for architectural (systems) and engineering studies. The methodology behind the Value Driven Design methodology as an outcome from the CRESCENDO EU project (Isaksson et al., 2013) following earlier works on Value Driven Design by e.g. (Collopy, 2006) and (Collopy and Hollingsworth, 2011). The Value Driven Design methodology offers the ability to compare the values of alternative concepts into high level expectations and alternative missions as demonstrated in (M. Panarotto et al., 2022). The VDD methodology has been implemented in a tool called Club Design (Panarotto et al, 2025).

4.5.6. Agentic Large Language Models in complex Engineering Design

Large Language Models (LLMs), and specifically agentic framework systems, support the engineers who aim to incorporate new design methods in their engineering activities. (Pradas Gómez et al., 2024). The support is applicable to all phases of the system development, from System Analysis to System Engineering, even though their exploration space is significantly different (Pradas Gómez et al., 2025).

Engineers focused on the design and development of systems come from a diverse set of backgrounds and are often unfamiliar with the state-of-the-art tools and methods that they could use. They are always constrained in terms of project deadlines and limited training support for tools. While subject matter experts are available at NASA and other companies, they are not readily available for the limited time window when the engineers could evaluate and test potential new methods. Large Language Model based applications are proposed as an intermediary between the engineer and the method. This can increase the adoption of new methods.

5. Insights and recommendations

The need for shorter lead times, while at the same time managing complex systems and emerging new technologies, necessitates rapid knowledge creation. The creation of knowledge entails building an understanding of how the system will behave during the operational phase, but notably also how to realize the concept through manufacturing. Since decisions made in the early design phase are responsible for a large portion of committed costs in a development process, there is much to gain from identifying risks early. Indeed, the earlier risks can be identified, the more design freedom is available to navigate around potential issues.

To gain the necessary knowledge to facilitate decision making in the early design phase, various systems modeling techniques can be used. A core idea in the EXPEED project is that the combination of tools developed in different contexts can yield novel insights. An example of this was demonstrated by combining Bayesian Network modeling with a E-FM model in Trinity of a design study previously conducted in the DIAS project.

The Bayesian Network model on the DIAS dataset complemented the evaluation of combined effects of design space variables to assess weld manufacturability. This resulted in non-trivial insights that was not originally discovered in the DIAS project. The Bayesian Network model interprets the observation of two variables together in the dataset as a joint effect, which can only be captured by highly advanced expert users of interactive visualization methods. Furthermore, the application of Bayesian networks in the DIAS project enabled querying the dataset to answer counterfactual questions ("What if" questions), facilitating an improved understanding of how changes in the design space were caused by changes in the variables of the problem. However, applying tools outside of their originally intended context is not without challenge.

When attempting to apply tools designed by different people for different purposes it is often necessary to extend the functionality of the tools to better suit the new context while being careful to avoid working beyond theoretical assumptions made in the tool. For instance, using MDAC to visualize data generated from Bayesian networks necessitated a means of visualizing data distributions. Naturally, additional functionality can broaden the applicability of a tool, though it comes at the cost of increased tool complexity. In other words, adding additional functionality may make it more difficult for a user to use the tool for its original purpose. Consequently, such extensions should be carefully considered beforehand. As a developer, it is thus important to raise the following questions: *i) Does the extended functionality add enough value to justify implementation?; and Will the new features get in the way of regular use?* If the answers to these questions are *no*, then perhaps the instantiation of a new tool should be considered, instead. It is necessary to revisit and understand the assumptions made on a dataset to use an analysis when reapplying other methods.

Combining multiple tools also heightens the need to carefully consider the original assumptions made in the development of each tool to avoid compounding errors when combining them. Some of the compounded errors can easily be hidden due to a lack of clear indications that errors are created, especially as the combined tool or method will still generate data. While the errors from each tool being used beyond its intended or accurate application may be small, compounding small errors, especially early in the system development lifecycle, can lead to critical dangers in a large-scale complex system. One of these dangers includes developing technical debt that creates hidden risks throughout the development cycle and makes the system less operationally resilient. Working beyond the operational envelope of a tool has chilling similarities to what was identified during the analysis of the NASA Challenger and Columbia disasters as "the normalization of deviance". (Vaughn, 1996; Smith, 2003) The deviance becomes the "new normal" and is accepted though still holding error.

Furthermore, one of the limitations identified was the limit in the multiplicity of the query variables. When querying with all the input design variables of the DIAS test case, the resulting probability distribution was uninformative. In other words, there was not a preferred portion of the design space that satisfied the requirements. This might be a consequence of either lack of sufficient data, insufficient infilling, or excessive degrees of freedom in the design space. This aspect has been highlighted when applying Bayesian Networks on an industrial-type problem, as within EXPEED.

Another challenge encountered during the course of the EXPEED project was the difference in semantics and nomenclature utilized by engineers from different fields and/or geo-location. This presents an initial barrier that needs to be surmounted before methods and tools can properly be re-contextualized. A clear example of this is how NASA labels different development life cycle stages (Cavanaugh et al, 2006) versus how classical engineering design literature (e.g., Pahl et al., 2007) refers to similar concepts.

Finally, the introduction of LLMs into the design activities introduces a new type of agency from a design automation perspective. Traditionally, the distribution of the activity ownership fell somewhere between the engineer and the available tools. Large Language Models can be used to decide which tool to use and how to use it, following a request from the engineer, and therefore bridging the gap between the engineer and the tool. This is only an observation through the EXPEED project, but the field is vast and developing very fast.

6. Conclusions

Design methodologies are typically developed and refined within specific disciplinary or organizational contexts. Consequently, assumptions, conventions, and terminology become embedded within these environments and are often regarded as self-evident.

The EXPEED exploratory study, which integrated design tools originating from diverse contexts, exposed ambiguities and raised critical questions when applied to a realistic reference case. The process of examining and discussing these underlying assumptions, conventions, and terminological differences provided valuable insights, fostering opportunities for renewal and for challenging established paradigms. Issues of manufacturability, highly significant for aircraft component manufacturers such as GKN, emerged as central considerations, given their direct implications for lead-time sensitivity and overall system-level performance. Novel manufacturing technologies, such as additive manufacturing, may also enable new product and system architecture and functionality. Hence, it is important to include such aspects early in system level studies.

Accordingly, it is essential not only to assess the validity and applicability of emerging approaches as they mature, but also to maintain a critical perspective on established practices. Seemingly minor details, such as the accessibility of welding equipment, may ultimately prove decisive in shaping future system solutions. As systems become more tightly integrated and complex, no single systems developer will be aware of all the best available tools for every problem. Being experienced in using one (type of) tool does not always encourage using other tools, where experience is lacking. Consequently, organizations and individuals face a challenge in how to adapt, challenge and learn to adopt new tools. For example, during the EXPEED project, OpenMDAO released several new tools relevant to the area of this study. A recommendation for further work is to encourage exploration of new potential tools and application these onto relevant complex reference datasets. It is important to learn the limits of validity and utility of new methods and tools. As the list of new tools continues to grow, it is relevant to ask how to develop the ecosystem of tools (Gericke et al., 2020).

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7. References

Cavanaugh, S., Kumar, A., Brewer, L., Kimmel, B., Korte, J., & Moul, T. (2006, January). Overview of NASA Langley's Systems Analysis Capabilities. In *11th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference* (p. 7025).

Clarkson, P. J., Simons, C., & Eckert, C. (2004). Predicting Change Propagation in Complex Design. Journal of Mechanical Design, 126 (5), 788–797. https://doi.org/10.1115/1.1765117

Collopy, P. (2006). Value-driven design & the global positioning system. In *Space 2006* (p. 7213).

Collopy, P. D., & Hollingsworth, P. M. (2011). Value-driven design. *Journal of aircraft*, *48*(3), 749-759.

EDC, C. (2025, September). *Cambridge Advanced Modeller* (Version v2). https://camtoolkit.eng.cam. ac.uk/

European Commission. (2012). Collaborative and Robust Engineering using Simulation Capability Enabling Next Design Optimisation (CRESCENDO). Retrieved August 25, 2025, from https:// cordis.europa.eu/project/id/234344/

European Commission. (2016). Thermal Overall Integrated Conception of Aircraft (TOICA). Retrieved August 25, 2025, from https://cordis.europa.eu/project/id/604981

European Commission. (2021). Consortium for Hall Effect Orbital Propulsion System (CHEOPS). Retrieved August 25, 2025, from https://cordis.europa.eu/project/id/730135

European Commission. (2023a). Development of Interdisciplinary Assessment for manufacturing and deSign (DIAS). Retrieved August 25, 2025, from https://cordis.europa.eu/project/id/887174

European Commission. (2023b). Future propulsion and integration: Towards a hybrid-electric 50-seat regional aircraft (FUTPRINT50). Retrieved August 25, 2025, from https://cordis.europa.eu/ project/id/875551

Georgiades, A., Sharma, S., Kipouros, T., & Savill, M. (2019). ADOPT: An augmented set-based de- sign framework with optimisation [Edition: 2019/03/07 Publisher: Cambridge University Press]. *Design Science*, *5*, e4. https://doi.org/10.1017/dsj.2019.1

Gericke, K., Eckert, C., Campean, F., Clarkson, P. J., Flening, E., Isaksson, O., Kipouros, T., Kokkolaras, M., Köhler, C., Panarotto, M., et al. (2020). Supporting designers: Moving from method menagerie to method ecosystem. *Design Science*, *6*, e21.

Gray, J. S., Hwang, J. T., Martins, J. R. R. A., Moore, K. T., & Naylor, B. A. (2019). OpenMDAO: An open-source framework for multidisciplinary design, analysis, and optimization. *Structural and Multidisciplinary Optimization*, *59*(4), 1075–1104. https://doi.org/10.1007/s00158-019-02211-z Isaksson, O., Kipouros, T., Martinsson, J., Panarotto, M., Kressin, J., Andersson, P., & Clarkson, J. P. (2021). Multi-Domain Design Assessment for Aerospace Components Including Weld Accessibility [Publisher: Cambridge University Press]. *Proceedings of the Design Society*, *1*, 2217–2226. https://doi.org/10.1017/pds.2021.483

Isaksson, O., Kossmann, M., Bertoni, M., Eres, M., Monceaux, A., Bertoni, A., Wiseall, S., & Zhang, X. (2013, June). *Value-Driven Design - A methodology to Link Expectations to Technical Requirements in the Extended Enterprise* (Vol. 23) [Journal Abbreviation: INCOSE International Symposium Publication Title: INCOSE International Symposium]. https://doi.org/10.1002/j.2334- 5837.2013.tb03055.x

Kim, T., Kipouros, T., Brintrup, A., Farnfield, J., & Di Pasquale, D. (2022). Optimisation of aero- manufacturing characteristics of aircraft ribs [Edition: 2022/02/08 Publisher: Cambridge University Press]. *The Aeronautical Journal*, *126* (1299), 866–888. https://doi.org/10.1017/aer.2021.113

Kipouros, T., & Isaksson, O. (2014). Integrating value assessment into the computational engineering design cycle, 3620.

Kipouros, T., & Isaksson, O. (2016). Visual analytics for evaluation of value impact in engineering design. ECCOMAS Congress, 9111.

Kipouros, T., Inselberg, A., Parks, G., & Savill, A. M. (2013). Parallel coordinates in computational engineering design. *54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, 1750.

Krupa, G., Spinelli, A., & Kipouros, T. (2023). An interactive framework to facilitate probabilistic set- based multidisciplinary design optimisation studies. *Journal of Physics: Conference Series*, *2526*, 012028. https://doi.org/10.1088/1742-6596/2526/1/012028

Panarotto, M., O. Isaksson, I. Habbassi, & N. Cornu. (2022). Value-Based Development Connecting Engineering and Business: A Case on Electric Space Propulsion. *IEEE Transactions on Engineering Management*, *69*(4), 1650–1663. https://doi.org/10.1109/TEM.2020.3029677

Martinsson Bonde, J. (2025a). *Trinity f-m modeler* (Version v1.7.0). Retrieved August 29, 2025, from https://trinity.martinsson-bonde.com/

Martinsson Bonde, J. (2025b, August). *Multidisciplinary Analysis Client (MDAC)* (Version v1.19.0). https://doi.org/10.5281/zenodo.6784231

Martinsson Bonde, J., Isaksson, O., Kipouros, T., Kokkolaras, M., & Andersson, P. (2025). Exploring design trade-offs among sustainability, performance, and manufacturability when considering integration of new technologies [Edition: 2025/08/27 Publisher: Cambridge University Press]. *Proceedings of the Design Society*, *5*, 1635–1644. https://doi.org/10.1017/pds.2025.10177

Martinsson Bonde, J., Isaksson, O., Panarotto, M., Andersson, P., & Kokkolaras, M. (2024). Similarity-based product family design for aero-engine components. *ISABE 2024*. https://doi.org/10.5281/ zenodo.14064084

Martinsson Bonde, J., Kokkolaras, M., Andersson, P., Panarotto, M., & Isaksson, O. (2023). A similarity-assisted multi-fidelity approach to conceptual design space exploration. *Computers in Industry*, *151*, 103957. https://doi.org/10.1016/j.compind.2023.103957

Martinsson Bonde, J., Brahma, A., Panarotto, M., Isaksson, O., Wärmefjord, K., Söderberg, R., Kipouros, T., Clarkson, P. J., Kressin, J., & Andersson, P. (2022). Assessment of weld manufacturability of alternative jet engine structural components through digital experiments. *ISABE 2022*. https://doi.org/10.5281/zenodo.7973381

McDonald, A., Robert, & Gloudemans, R., James. (2022). Open vehicle sketch pad: An open source parametric geometry and analysis tool for conceptual aircraft design. *AIAA SCITECH 2022 Forum*, 0004. https://doi.org/10.2514/6.2022-0004

McDonald, A., Robert, & Gloudemans, R., James. (2025, September). *OpenVSP* (Version v3.45.4). https://doi.org/10.2514/6.2022-0004

Müller, J. R., Isaksson, O., Landahl, J., Raja, V., Panarotto, M., Levandowski, C., & Raudberget, D. (2019). Enhanced function-means modeling supporting design space exploration [Publisher: Cambridge University Press]. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM*, *33* (4), 502–516. https://doi.org/10.1017/S0890060419000271

NASA. (2016). *NASA systems engineering handbook* (Rev 2). https://www.nasa.gov/reference/systems-engineering-handbook/

Pahl, G., Beitz, W., Feldhusen, J., & Harriman, R. A. (2007). *Engineering Design: A Systematic Approach* (3rd ed.). Springer.

Panarotto M, Isaksson O, Andersson P. Value-driven MBSE for evolving business contexts: a quantitative study on aerospace electrification. *Design Science*. 2025;11:e36. doi:10.1017/dsj.2025.10024

Piotrowski, W., Kipouros, T., & Clarkson, P. J. (2019). Enhanced Interactive Parallel Coordinates using Machine Learning and Uncertainty Propagation for Engineering Design. *2019 15th International Conference on eScience (eScience)*, 339–348. https://doi.org/10.1109/eScience.2019.00045

Pradas Gomez, A., Krus, P., Panarotto, M., & Isaksson, O. (2024). Large language models in complex system design. *Proceedings of the Design Society*, *4*, 2197–2206. https://doi.org/10.1017/pds. 2024.222

Pradas Gómez, A., Panarotto, M., & Isaksson, O. (2025). Fuse: A novel design space exploration method for aero engine components that combines functional and physical domains. *Aerospace*, *12* (1). https://doi.org/10.3390/aerospace12010051

Raudberget, D., Levandowski, C., Isaksson, O., Kipouros, T., Johannesson, H., & Clarkson, J. (2015). Modelling and assessing platform architectures in pre-embodiment phases through set-based evaluation and change propagation [Publisher: SAGE Publications]. *Journal of Aerospace Operations*, *3* (3-4), 203–221. https://doi.org/10.3233/AOP-150052

Smith, M. S. (2003). NASA's space shuttle Columbia: Synopsis of the report of the Columbia accident investigation board (No. CRS-RS21408).

Spinelli, A., Krupa, G., Kipouros, T., Laskaridis, P., & Berseneff, B. (2025). Battery pack technological considerations for hybrid-electric regional aircraft feasibility [Edition: 2025/01/28 Publisher: Cambridge University Press]. *The Aeronautical Journal*, 1–25. https://doi.org/10.1017/aer. 2024.140

Spinelli, A., & Kipouros, T. (2023a). *Probabilistic Design and OPTimisation framework (PDOPT)* (Version v0.5). Retrieved August 29, 2025, from https://github.com/spinjet/pdopt-code/

Spinelli, A., & Kipouros, T. (2023b). *PDOPT Decision Making Tool* (Version v0.1). Retrieved September 28, 2025, from https://github.com/spinjet/dm_tool

Spinelli, A., & Kipouros, T. (2025). *Probabilistic Design and OPTimisation framework (PDOPT) - Bayesian Network branch* (Version v0.6). Retrieved August 29, 2025, from https://github.com/spinjet/pdopt-code/tree/bayesian network

Spinelli, A., Enalou, H. B., Zaghari, B., Kipouros, T., & Laskaridis, P. (2022). Application of Probabilistic Set-Based Design Exploration on the Energy Management of a Hybrid-Electric Aircraft. *Aerospace*, *9* (3). https://doi.org/10.3390/aerospace9030147

Spinelli, A., & Kipouros, T. (2024). PDOPT: A Python library for Probabilistic Design space exploration and OPTimisation. *Journal of Open Source Software*, *9* (95), 6110. https://doi.org/10.21105/ joss.06110

Spinelli, A., & Kipouros, T. (2025a). Use of Bayesian Networks to Understand Sustainability Requirements. *Engineering Proceedings*, *90* (1). https://doi.org/10.3390/engproc2025090032

Spinelli, A., & Kipouros, T. (2025b, January). Aircraft Design System Requirements Analysis With Bayesian Networks. In *AIAA SCITECH 2025 Forum*. American Institute of Aeronautics; Astronautics. https://doi.org/10.2514/6.2025-2032

Spinelli, A., Krupa, G., & Kipouros, T. (2023a). A system-based approach for technology roadmapping assisted by visual analytics. *Aerobest 2023 - II ECCOMAS Thematic Conference on Multidisciplinary Design Optimization of Aerospace Systems*, 222–238.

Spinelli, A., Krupa, G., Kipouros, T., Berseneff, B., & Fiette, S. (2023b). Investigation of the operational flexibility of a regional hybrid-electric aircraft. *Journal of Physics: Conference Series*, *2526*, 012021. https://doi.org/10.1088/1742-6596/2526/1/012021

Spinelli, A., Krupa, G. P., & Kipouros, T. (2023c, January). Set-Based Design Space Exploration to Investigate the Effect of Energy Storage Durability on the Energy Management Strategy of a Hybrid-Electric Aircraft. In *AIAA SCITECH 2023 Forum*. American Institute of Aeronautics; Astronautics. https://doi.org/10.2514/6.2023-0837

Spinelli, A., Sharma, A., & Kipouros, T. (2024, September). Requirements Uncertainty Propagation in Conceptual Design using Bayesian Networks. In *ICAS proceedings. 34th congress of the interna- tional council of the aeronautical sciences*. International Council of the Aeronautical Sciences (ICAS).

UKRI. (2020). Advanced Product Concept Analysis Environment (APROCONE). Retrieved August 25, 2025, from https://gtr.ukri.org/projects?ref=113092

UKRI. (2025). Out of Cycle NExt generation highly efficient air transport (ONEheart). Retrieved August 25, 2025, from https://gtr.ukri.org/projects?ref=10003388

Vaughan, D. (1996). The Challenger launch decision: Risky technology, culture, and deviance at NASA. University of Chicago press.

Vinnova. (2024). Development of efficient DIgital product FAMily design platform to increase cost efficiency - DIFAM — Vinnova. Retrieved August 25, 2025, from https://www.vinnova.se/p/ development-of-efficient-digital-product-family-design-platform-to-increase-cost-efficiency--- difam/